SCIENCE RESEARCH & PROJECTS DIVISION/ST10

X-Ray Optics at MSFC

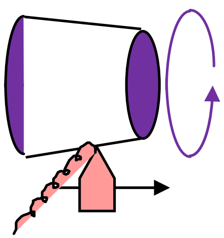
Brian Ramsey, Steve Bongiorno, Dave Broadway

Outline

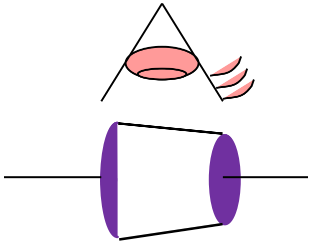
1. Electroformed nickel replication (ENR)– Brian Ramsey
2. Computer-controlled polishing – Steve Bongiorno
3. Full shell optics by direct fabrication – Steve Bongiorno
4. Differential deposition – Brian Ramsey
5. Low-stress coatings – Dave Broadway
6. X-ray optics process flow / Conclusion – Steve Bongiorno

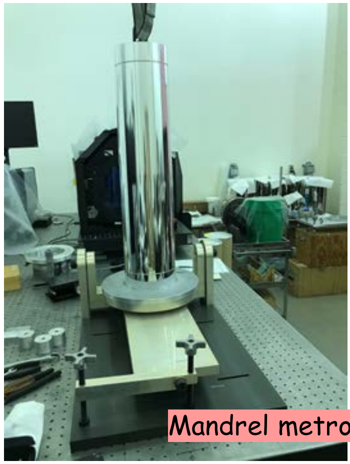
Electroformed Nickel Replication (ENR)

Mandrel - machining Al bar, electroless nickel coating, diamond turning and polishing

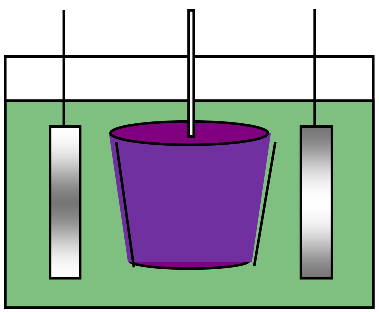


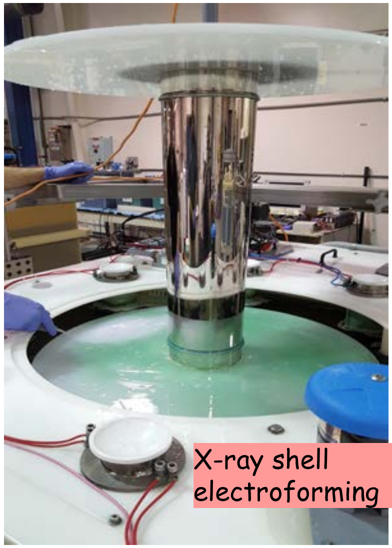
Metrology on mandrel



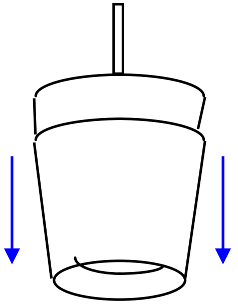


Electroform Ni/Co shell onto mandrel



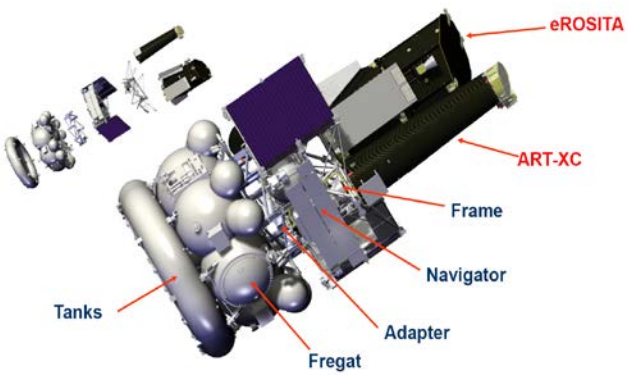


Separate optic from mandrel in cold water bath

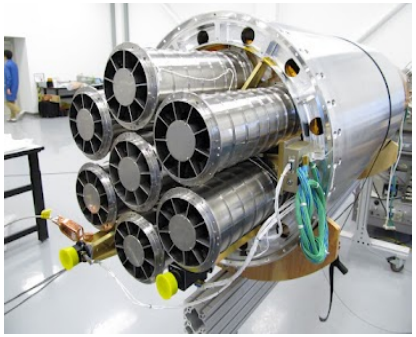


ENR– Current and Recent Programs

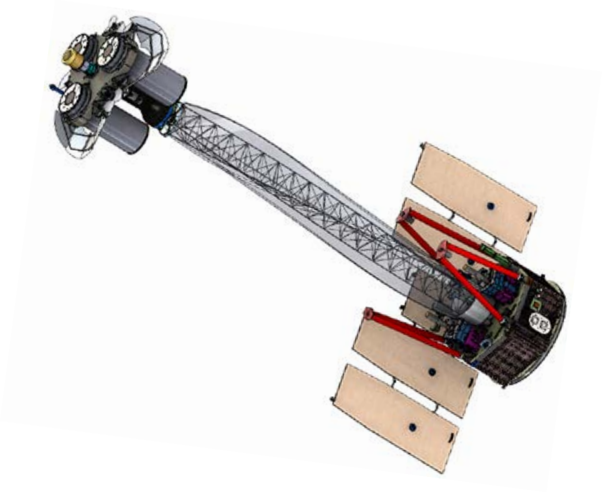
ART-XC instrument on Spectrum Rontgen Gamma Mission



FOXSI (Rocket)

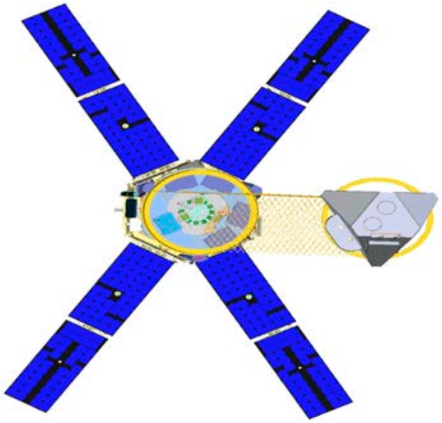


IXPE Small Explorer



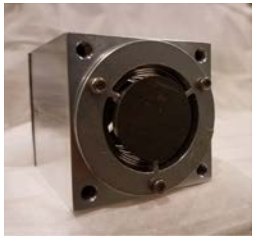
HERO

FOXSI Small Explorer (Phase A study)

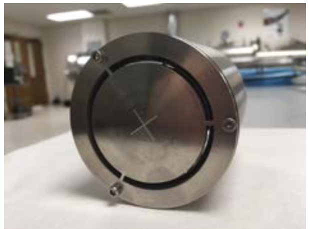


Non-Astronomical Applications

Neutron Imaging



Plasma Diagnostics



X-ray optics at MSFC

New Developments

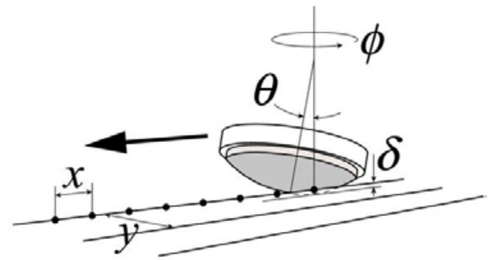
Computer Controlled (CC) Polishing

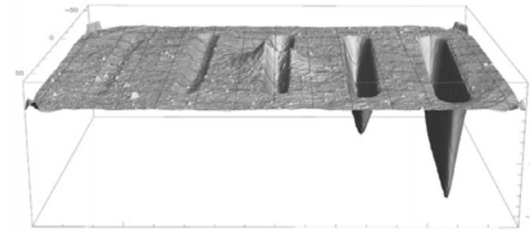
Challenge
- The optical figure of mandrels used to produce replicated nickel cobalt grazing incidence optics directly impacts performance of the optic.

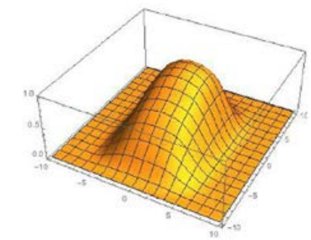
Objective
- Reach sub-arcsecond half-power diameter (HPD) mandrel figure error to enable future missions.

Approach:
- Test methods for aligning Zeeko CC polishing machine coordinates with mandrel coordinates with mandrel fiducials.
- Continue improving surface roughness and polishing wear function stability by adjusting abrasive slurry parameters.
- Polish mandrels with Zeeko machine for shape correction and super polish with large laps to achieve final surface roughness.
- Estimate finished mandrel performance with mandrel metrology on Zygo interferometer at MSFC.

Computer Controlled (CC) Polishing

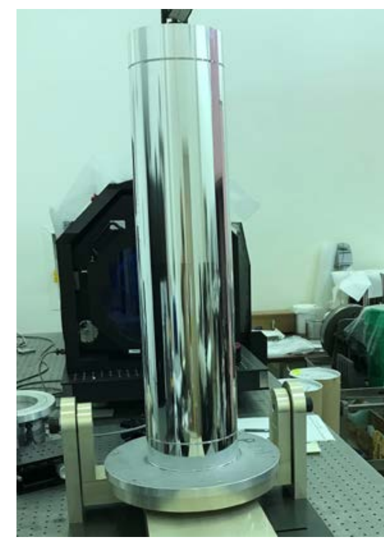






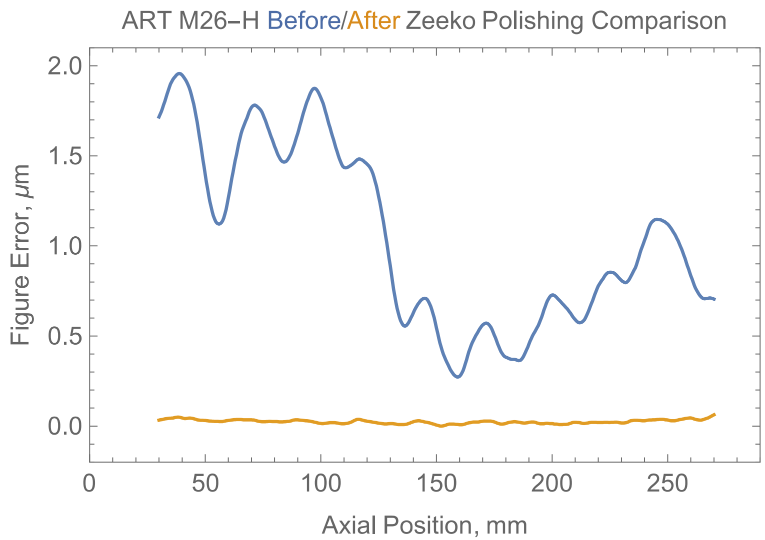
CC polishing process loop

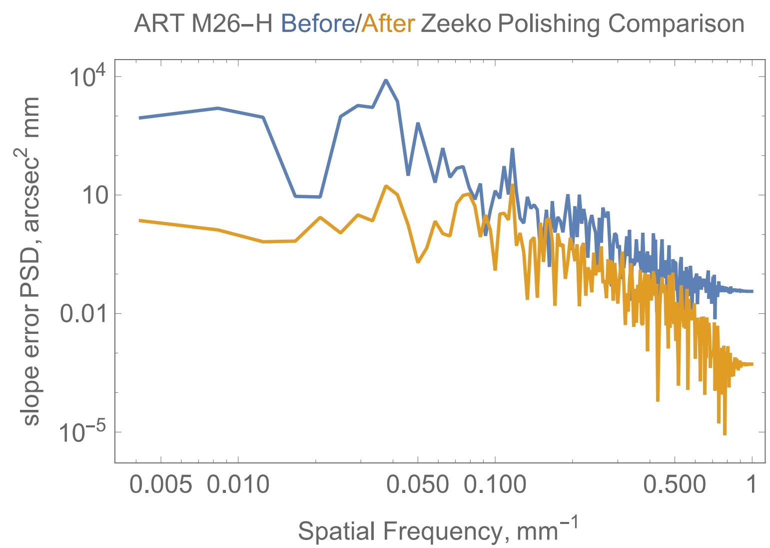
1. Characterize machine/bonnet wear function
2. Map optic/mandrel surface error
3. Deconvolve surface error map with wear function to generate toolpath
4. Polish optic
5. Iterate



Computer Controlled (CC) Polishing ART M26H

Cylindrical Correction Complete, azimuthal average, Polishing time: 71.5 hours





	before	after
Figure error (St. Dev.)	500 nm	10.7 nm
Slope error (> 2 cm) (RMS)	6.32 arcsec	0.30 arcsec
Low frequency (> 7 cm) slope error (RMS)	2.66 arcsec	0.09 arcsec
Mid frequency (2-7 cm) slope error (RMS)	5.73 arcsec	0.29 arcsec

Full width at half max ≈ 6.66 * RMS slope error = 2.00 arcsec

Computer Controlled (CC) Polishing

TRL Level

Currently at ~ 3

Challenges and future work

- Complete test mandrel polishing and quantify surface quality improvement.

Applicable to Athena

Yes, for direct polishing of full-shell optics.

Thin-shell direct fabrication

Challenge

- Future X-ray missions require large effective area, lightweight, high angular resolution grazing incidence optics.

Objective

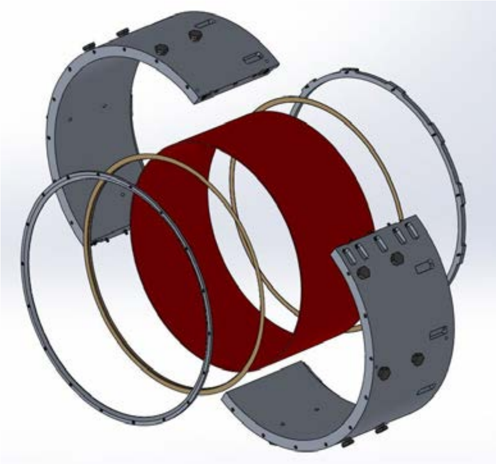
- Using high specific stiffness metal materials (Be, AlSi, AlBe), produce sub-arcsecond grazing incidence full-shell optics approximately 3 mm thick.

Approach:

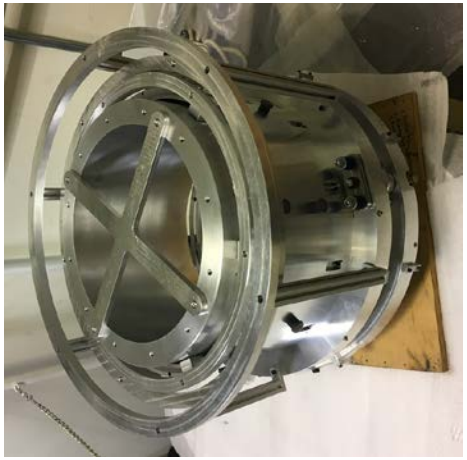
- Diamond turn inner and outer surface of as-purchased metal/metal-composite shells.
- Implement in-situ metrology to measure the shape of the shell while mounted in the polishing machine.
- Directly polish shells in the Zeeko machine at MSFC.
- If needed, apply differential deposition in chamber at MSFC to improve mid-spatial frequency shape error.

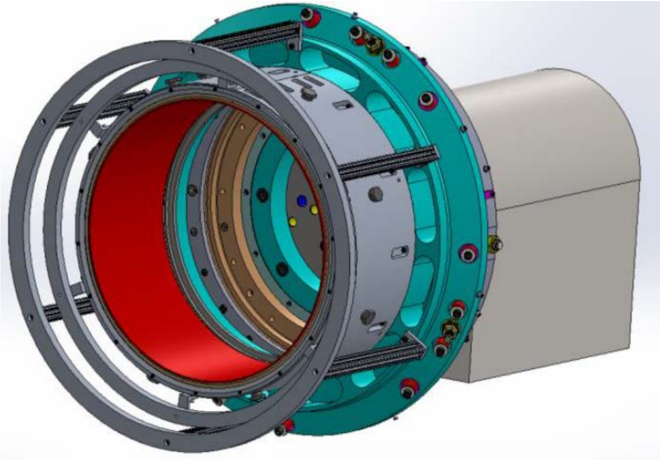
Thin-shell direct fabrication

Aluminum surrogate shell



Shell support structure





Shell support structure mounted to diamond turning machine

Thin-shell direct fabrication

TRL Level

Currently at ~ 2

Challenges and future work

- Delivery of 3 mm thick figured and polished NiP plated aluminum shell
- Design of X-ray test support fixture, and cross-calibrated verification of in-situ metrology system. Delivery of X-ray test support fixture and verification of the 3 mm and 1.5 mm thick mirrors via X-ray testing.

Applicable to Athena

Yes, for direct polishing of full-shell optics.

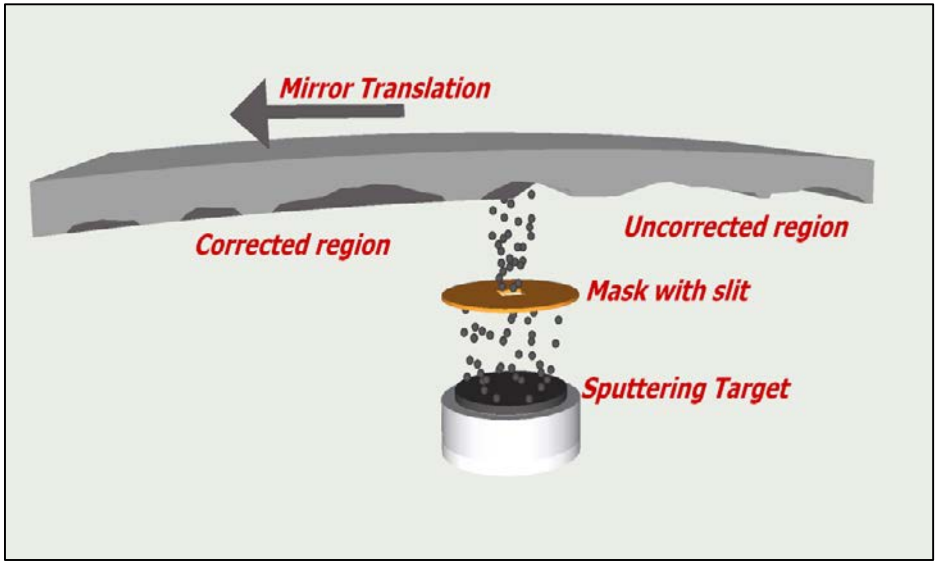
Differential Deposition - Overview

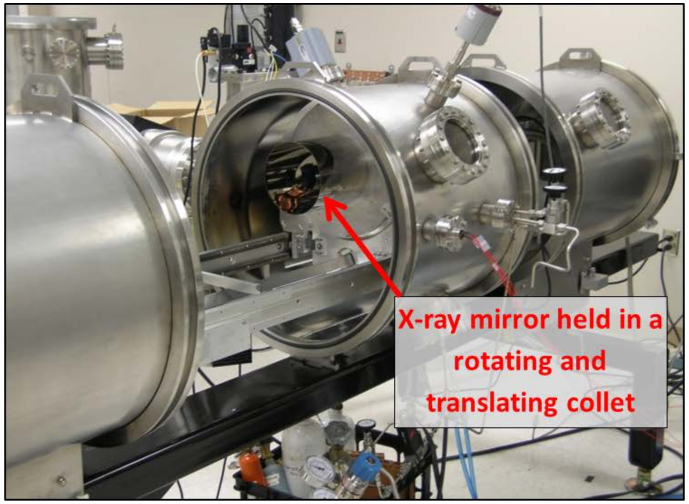
Objective

Develop a process to provide post-fabrication improvement to x-ray optics

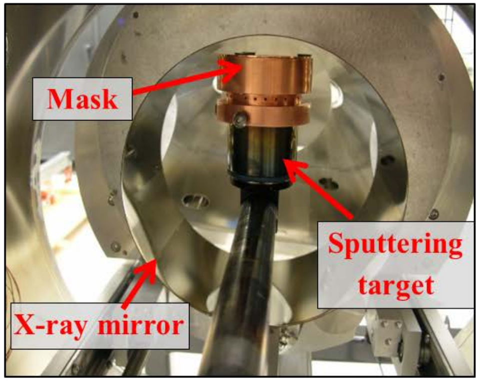
Approach

Use physical vapor deposition to selectively deposit material on mirror surface to reduce figure errors

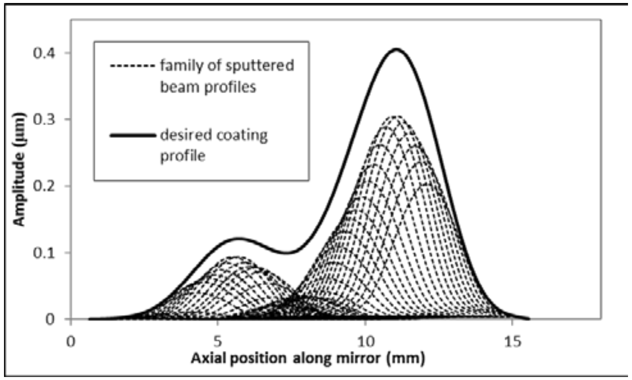




Horizontal differential-deposition chamber

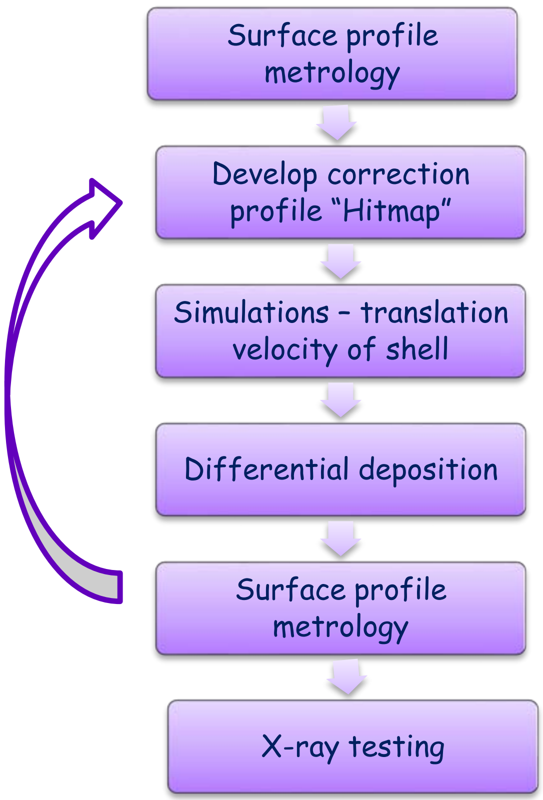


Sputtering head with copper mask positioned inside shell

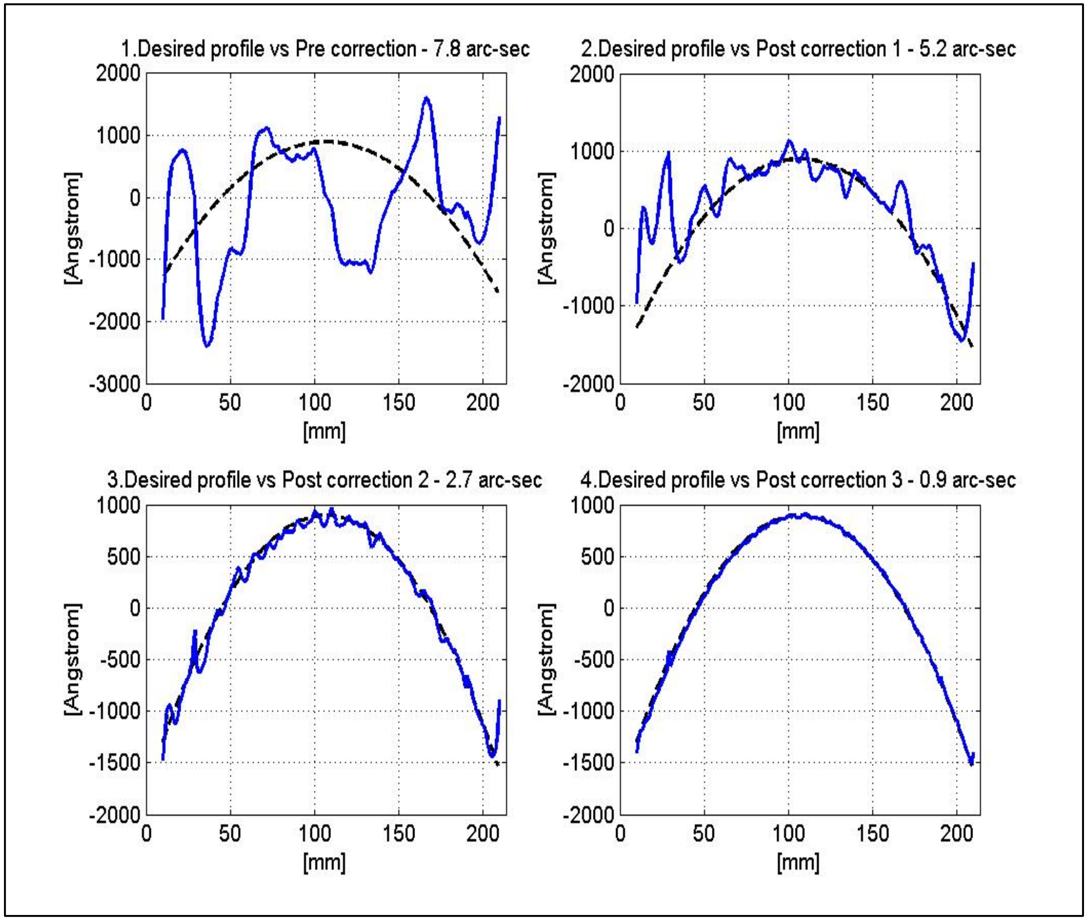


Differential Deposition - Process

Differential deposition process flow

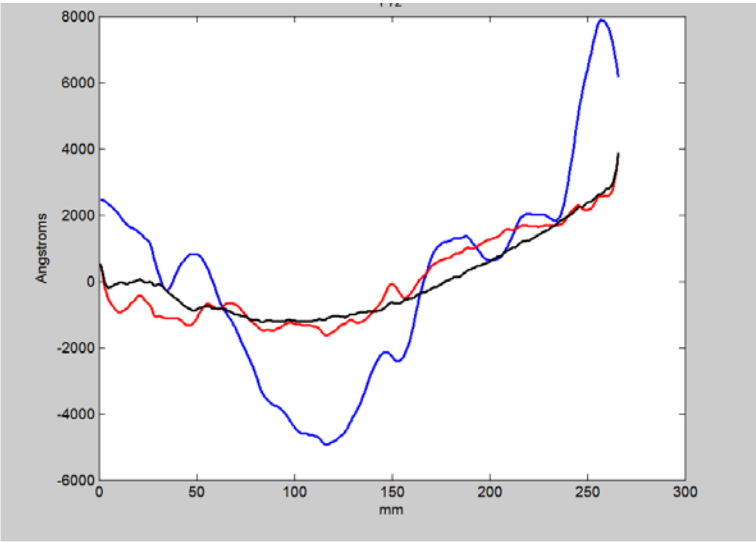


Simulation of successive corrections with finer slits

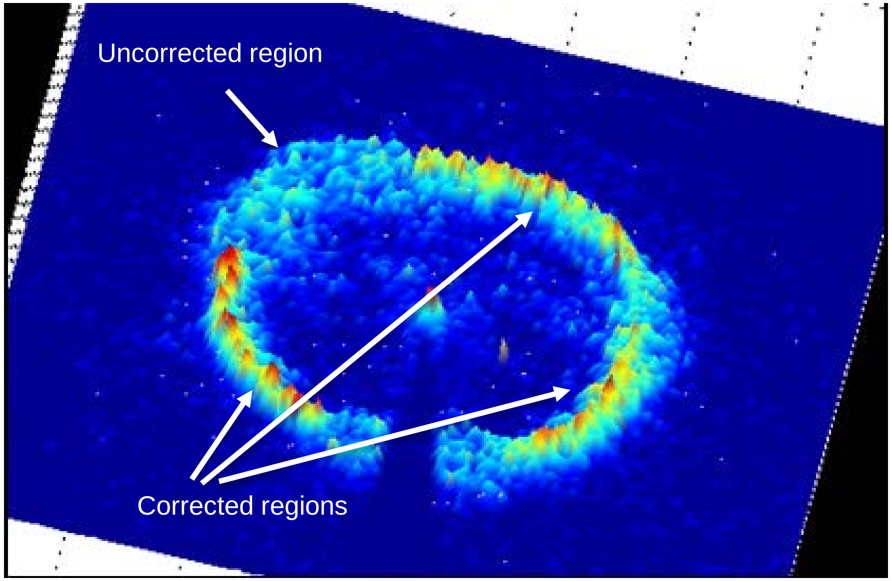


Differential Deposition - Results

Axial figure profiles: Initial (blue), after 1 correction pass (red), after 2 correction passes (black)



Intra-focus x-ray image showing uncorrected and corrected mirror quadrants



- Using ART-XC mirror shells , have obtained a factor of > 2 improvement in agular resolution for a single stage of correction from 17 arcsec to 7.2 arcsec HPD.
- Metrology on mirror shell with 2 stages of correction shows factor of 3 improvement from 17 arcsec to 5 arcsec HPD.

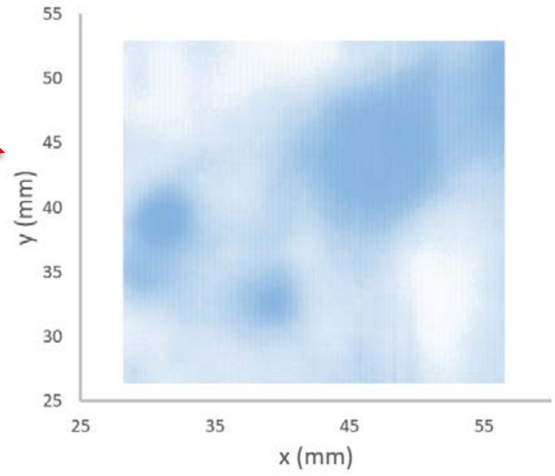
Differential Deposition

TRL Level

Currently at ~ 3

Challenges and future work

- Assess coating-stress effects.
- Implement active slits to compensate for change of internal diameter of shell with length (less of a challenge for large-diameter optics)
- Develop in-situ metrology
- Develop custom masks for rapid correction



Applicable to Athena

Yes, for figure control of full shell (or segmented) optics.

Thin Film Coatings- Overview

Challenge

- Small amounts of coating stress can significantly distort a large thin-shell optic.
  - Preservation of substrate figure after deposition of x-ray reflective coatings is a leading technological challenge.

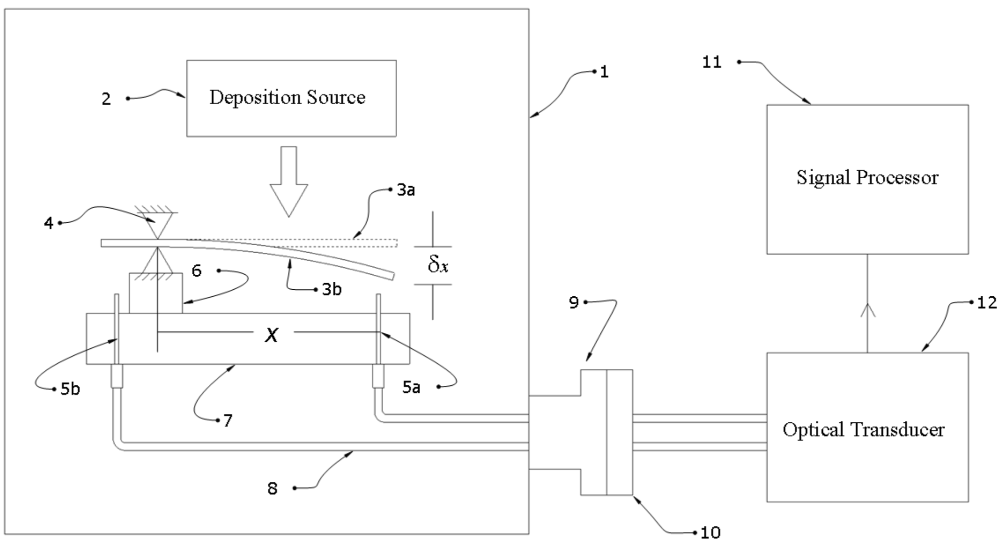
Objective

- Develop advanced low stress x-ray optical coatings (single-layer and multi-layer) that will enable future missions.

Approach:

- The use of a proven novel highly-sensitive method of in-situ stress measurement that will be adapted to curved substrates.
  - Investigate stress growth in films and methods for its reduction.
- The design and implementation of a novel single and multilayer coating scheme for achieving inherently uniform coatings on flat and curved segments.

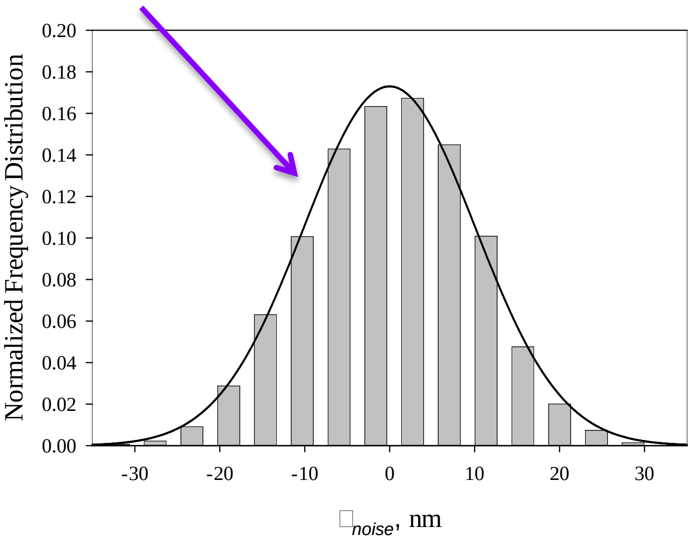
Thin Film Coatings- In-Situ Stress Measurement Method



- Film stress deforms figured substrates and degrades imaging resolution.
- We measure stress in-situ using a high resolution (i.e. 5 nm) fiber optic displacement sensor.
- The sensor measures the cantilever tip deflection caused by the film stress which is calculated using the Stoney Eqn:

$$\sigma h_f = \frac{E_s h_s^2 \delta_x}{3(1-\nu_s)x^2}$$

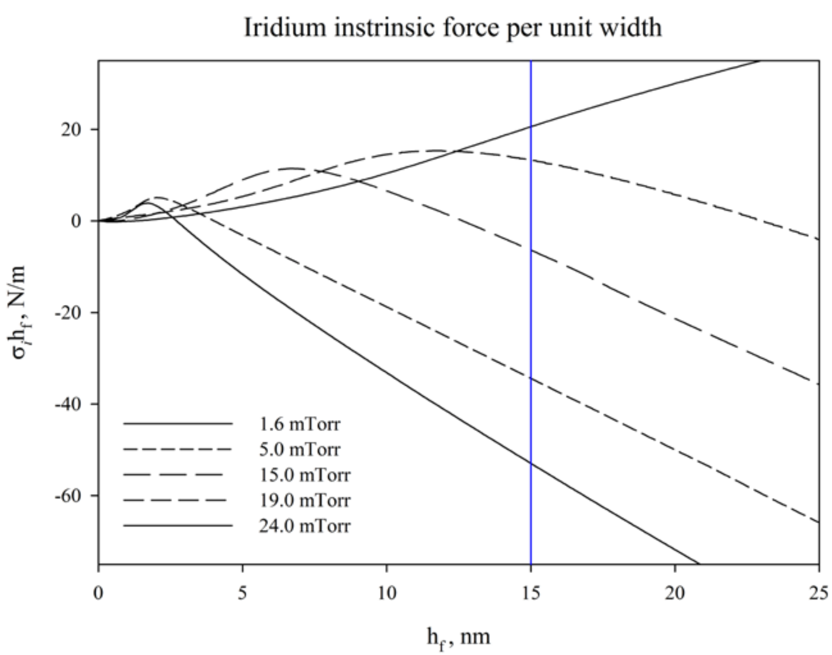
25 MPa*nm sensitivity



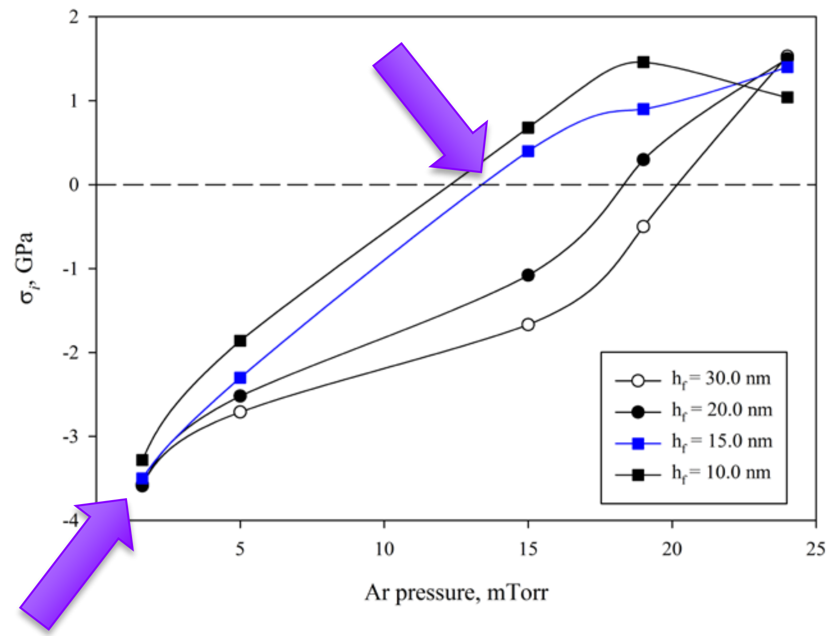
X-ray optics at MSFC

Thin Film Coatings- Zero Stress Iridium

- The requirements for missions are typically satisfied with 10-20 nm of Ir
- Through Ar pressure optimization we can reduce the stress to near zero (measured 3 orders of magnitude decrease)
- Surface roughness increases from 3 to 4.5Å



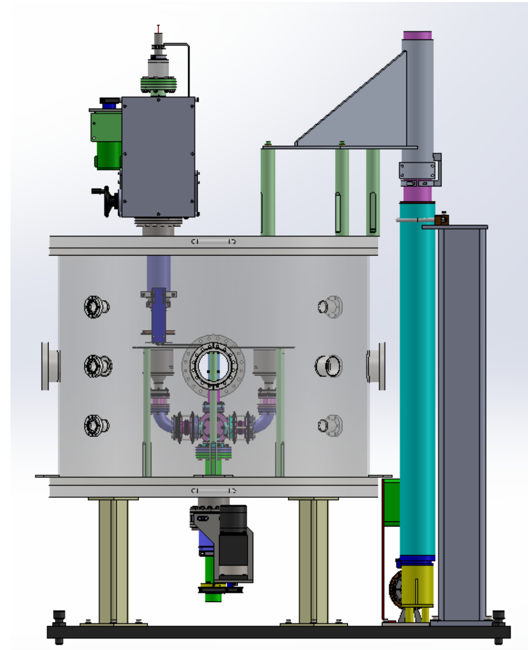
~ Zero stress

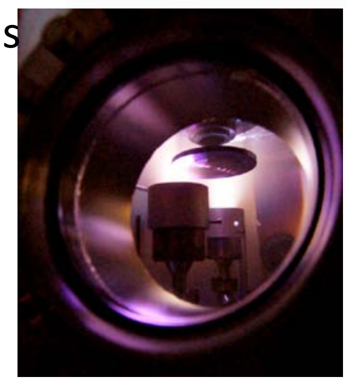


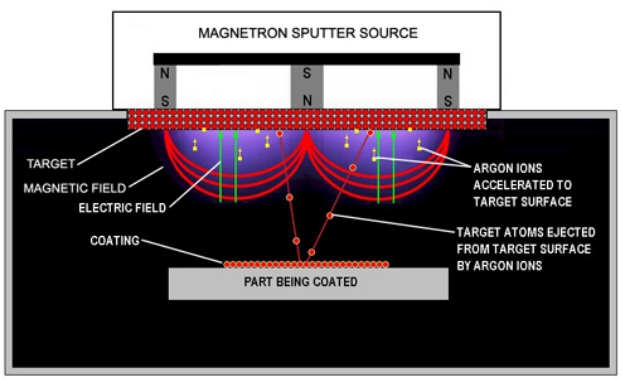
-3.7 GPa

Thin Film Coatings- Capability at MSFC

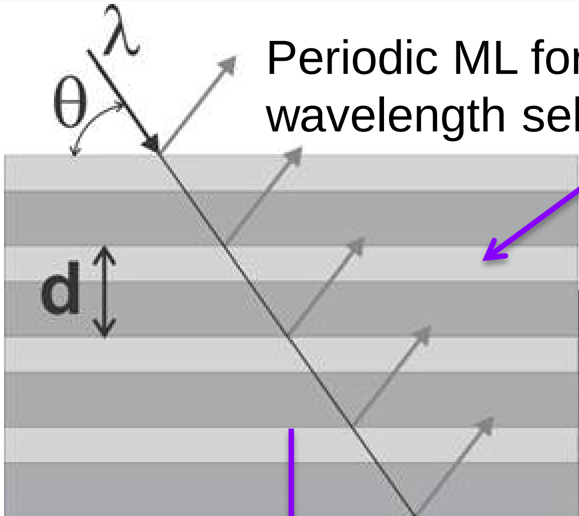
- Procured with MSFC innovation funding (CIF) award
- For development of depth graded ML's
  Designed for flexibility in deposition geometry
- Currently utilizes up to four 2 in. dia. circular cathode positions
- Ion milling capability
- Spinning substrate holder
  - Holds up to 4 inch dia. substrates
  - Bias can be applied
- Future work includes system upgrade to expand capability to coat segmented substrates



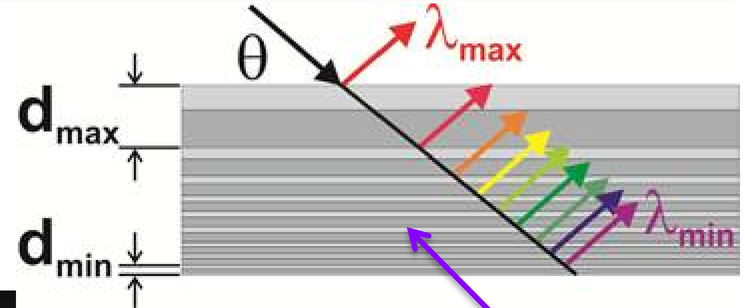




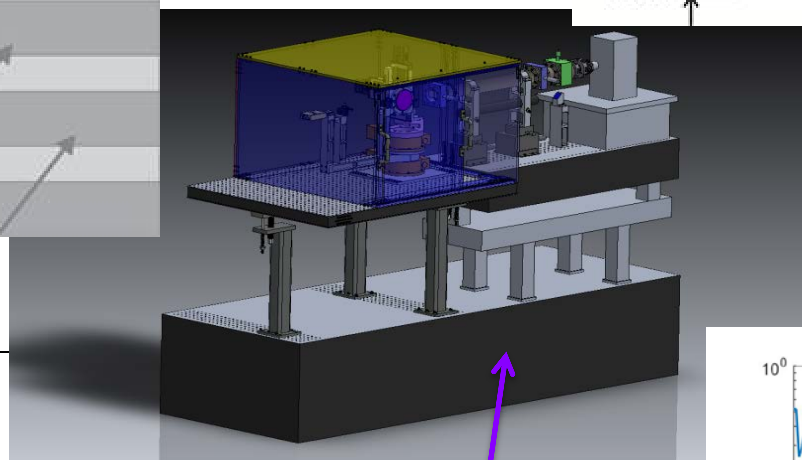
Thin Film Coatings- Measurement



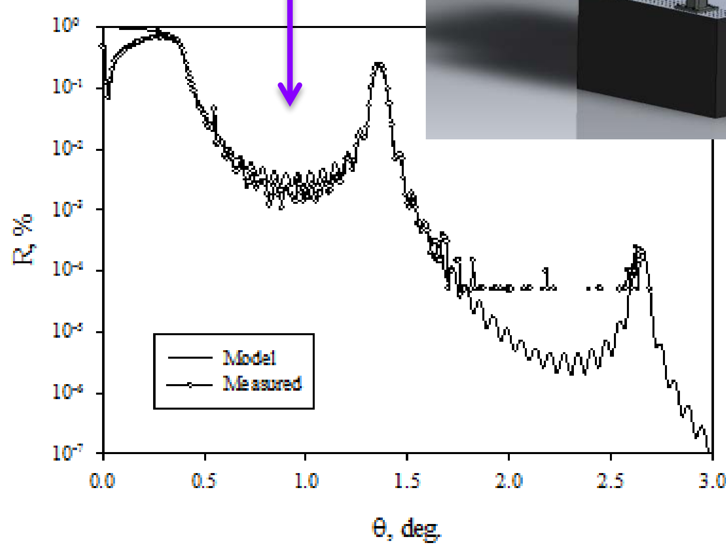
Periodic ML for high resolution wavelength selective applications

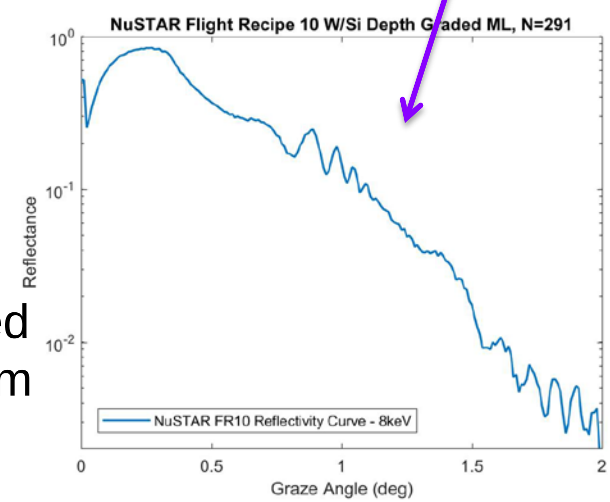


Depth graded ML for broadband response



MSFC X-Ray Reflectometer used to measure thin film properties





X-ray optics at MSFC

Thin Film Coatings

TRL Level
Currently at ~ 3

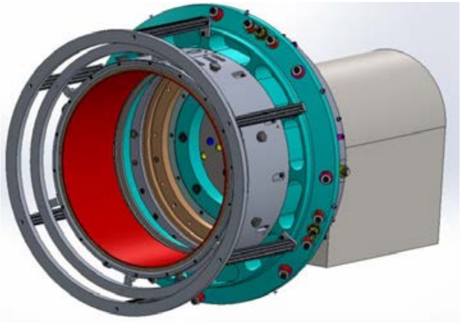
Accomplishments
- Reduced iridium coating stress by three orders of magnitude by exploiting the film's growth mechanism that was revealed by in-situ stress measurement capability.
- Demonstrated approach for achieving targeted reflectivity response of the depth graded multilayer coatings.

Challenges and future work
- Completion of new deposition system design to enable the coating and in-situ stress measurement of curved optical segments
- Development of in-situ stress measurement during thermal annealing processes

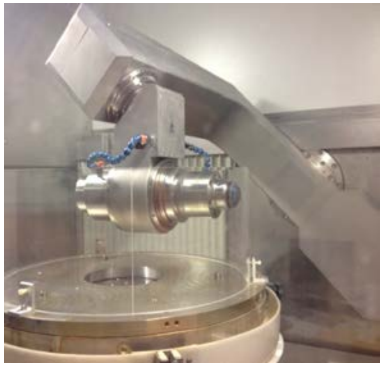
Applicable to Athena :
Yes, to maintain figure of full shell (or segmented) optics.

Full-shell Optic Fabrication Process Applicable to Athena

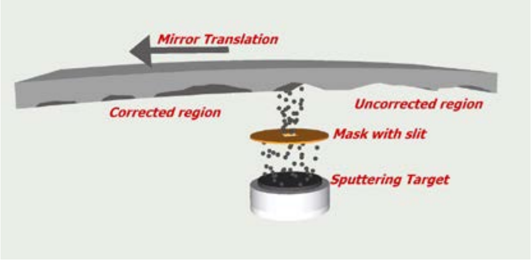
Machined mirror blanks



Diamond turning
TRL~2



Computer controlled polishing
TRL~3



Differential deposition
TRL~3

Low-stress reflective
coatings
TRL~3

Alignment and module integration
TRL~3

X-ray optics at MSFC